

EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION
NOTE VII: ANALYSIS OF THE PERFORMANCE OF AN ARCJET DRIVEN BY
HYDROGEN AND NITROGEN

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EXPERIMENTAL RESEARCH ON ELECTRIC PROPULSION

NOTE VII: ANALYSIS OF THE PERFORMANCE OF AN ARCJET DRIVEN BY
HYDROGEN AND NITROGENAurelio C. Robotti and Mario Oggero¹

ABSTRACT

Description of experiments performed on a new type of arcjet, characterized by composite electromagnetic and vortex stabilization and propelled by hydrogen and nitrogen in turn. Particular attention was devoted to the electrical characteristics of the arc and to the loss of heat through electrodes.

1. Introduction.

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When research was undertaken by this School in 1960 on arcjets, the planning and development of a hydrogen-driven arcjet presented considerable difficulty. Therefore, initial studies used inert gases such as nitrogen, air and argon, which held little interest for propulsion purposes, but served as orientation.

*Numbers given in margin indicate pagination in original foreign text.

¹Work presented by Prof. Aurelio C. Robotti, School of Aerospace Engineering, Torino Polytechnical School. Work conducted with the assistance of the CNR.

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The experimental results obtained in this first phase of research were published in various Notes (refs. 1-3).

They furnished useful information on the behavior of the electric arc in the presence of magnetic and aerodynamic fields, and permitted us to determine the best geometry for the electrodes, both from the point of view of their consumption and of their thermal exchange.

A new arcjet adapted for hydrogen as a propellant passed from the planning to the experimental stage, and showed prospects of success.

Subsequently, the same arcjet was driven by nitrogen, in order to compare the results of tests with hydrogen.

2. Experimental Apparatus.

Figure 1 shows schematic of the hydrogen arcjet. With regard to previous models designed for nitrogen and argon, this shows the distance between electrodes reduced one third in order to increase the stability of the arc. /895 The dimensions of the chamber are therefore very small in comparison with the nitrogen and argon arcjets. The central electrode has, however, the same dimensions and is interchangeable with those of the previously constructed models.

The arc is stabilized principally by a vortex created by the intake feed gas which is injected tangentially to the chamber; moreover, on the base of the arcjet, a winding is mounted along the path of the arc current which also produces an electromagnetic stabilizing effect especially useful in the initial transient current when the vortex is not yet efficient.

Water circulation cools the electrodes; the capacity is 0.5 liter/sec for the anode, and 0.4 liter/sec for the cathode. The winding of the magnetic field is also water-cooled.

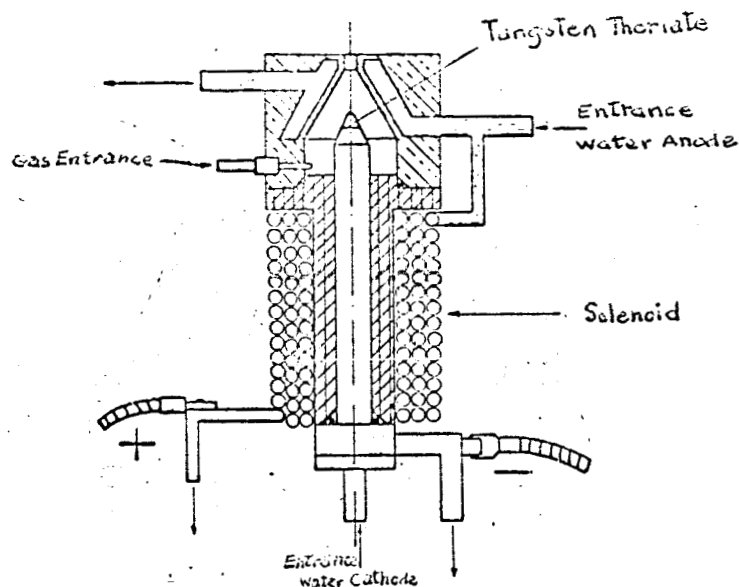


Figure 1. Diagram of the hydrogen arcjet.

Figure 2 shows the general plan of the feed installation. The continuous current is supplied by a three-phase, 220V, silicon rectifier junction, through a three-way (220, 190, and 150V) transformer which permits selecting the most suitable voltage for the installation; it functions by an arc circuit separator from the feed line.

Cooling is of the closed circuit type, with a 1 m³ tank of a capacity permitting prolonged tests to be made without a noticeable increase in water temperature. Circulation is provided by a pump with a maximum capacity of 5 liter/sec and a pump head of 40 m.

All operations are by remote control through a remote control switch; all controls are mounted on a single control board. The arcjet was set up to avoid danger of an accidental gas escape.

3. Instrumentation.

In addition to the normal electrical measurements of voltage and current, the arcjet was provided with temperature detectors at the entrance and exit of

the cooling ducts. Thermocouple and thermoresistance detectors were used for this purpose in various tests; in the case of the thermocouple detector, due to the slight increase in water temperature, the sensitivity was increased by adding junctions in series, with a cold coupling in the water of the entrance cooling duct, in order to permit direct reading of a difference in temperature.

The accuracy and duplication of both measuring methods are about equal; the thermoresistance detectors used in junction series are more sensitive, but show a considerably longer response time. For this reason, they should be 1896 limited to tests at operating speed, for specified times.

Measurement of the cooling water capacity was made with a Venturi meter inserted in the bypass; the hydrogen capacity is measured then with a diaphragm flow meter, calibrated previously by comparison with a rotameter.

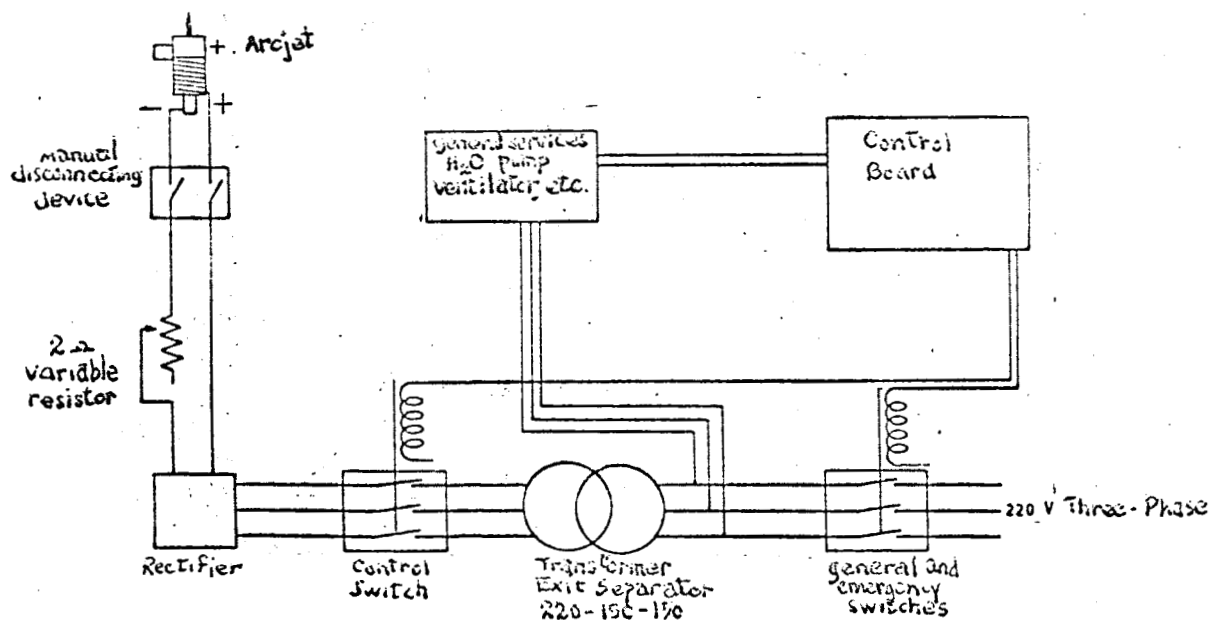


Figure 2. General installation plan.

4. Experimental results.

4.1. Tests with Hydrogen

Experiments were started with the new hydrogen arcjet in order to gather, with as few tests as possible, a first group of data easily interpreted on the basis of previously obtained results. This was done using single variable; in particular, the behavior of the arcjet was studied by varying the gas capacity, maintaining constant both the current and the geometry of the chamber. Moreover, a nozzle with a rather large (about 4 mm) diameter was selected so that the pressure of the arc could be kept constant and equal to atmospheric pressure throughout the field being measured.

In the first series of tests, current levels of 200 A and 160 A were examined, using both hydrogen and nitrogen.

In the case of hydrogen (fig. 3), the arc voltage tends to increase considerably, equal to the current, with the capacity of gas; this voltage increase is accompanied by a variation of the geometry of the arc which can be observed during the tests.

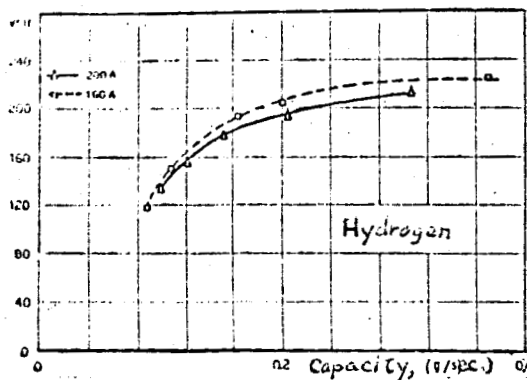


Figure 3. Voltage-capacity curve in the hydrogen arcjet.

At lower capacities, the electric arc strikes the inside of the chamber and the anode base rests approximately in the nozzle converging zone, as shown in figure 4. This is confirmed by the very obvious traces which can be observed in a high test chamber. /897

As the capacity increases, the arc rises up in the flue and at a specified value becomes stabilized in harmony with the outer edge; in this position the arc can be easily seen through proper screens and appears like a luminous nucleus centered on the nozzle.

By later increasing the capacity, the arc extends on the outside, as if it were discharged, but the position of rest in the chamber does not change in harmony with the outer edge of the nozzle.

The erosion of the nozzle walls is clearly related to the geometry of the arc; at high capacities an erosion can be seen in the form of a crater near the end of the nozzle where the base of the arc rests.

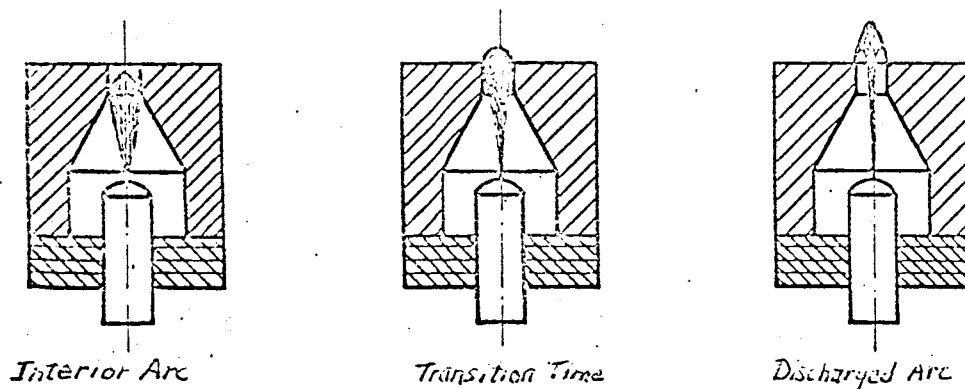


Figure 4 Configurations of the arc.

At lower current, the phenomenon of the arc discharge or blowoff tends to take place at lower levels of capacity; the voltages increase noticeably and the arc becomes unstable. At currents on the order of 140 A the arc can be burnt out quite easily.

4.2. Tests with nitrogen.

The test at 200 A and 160 A were repeated with nitrogen at the molar heat content level on the order of magnitude of hydrogen to provide similar conditions of heat supply to the gas; hence in the first approximation and without disassociation, there is equal average temperature of gas.

In the case of nitrogen, the arc tension or voltage is less than for hydrogen (compare with figure 5), but it preserves a perfectly analogous characteristic: only in this case can the displacement of the arc be observed at the increase in capacity and consequent outside discharge, for greater values, but in the case of nitrogen the arc is much more stable and throughout the tests a spontaneous burnout or extinction is never observed

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5. Calorimetric measurements.

Temperature data at the entrance and exit of separate ducts of the cooling circuit permitted an evaluation to be made of thermal loss in the individual electrodes; as a result, the loss of efficiency could be evaluated due to heat transfer at the walls

$$1- \eta = W_p/W$$

where W = electric power supplied: $V \cdot I$

W_p = the sum of the power lost in the cooling of the two electrodes; it is noted that η in the first approximation can be assumed to be equal to the efficiency or yield of the conversion of electric energy into the thermal energy of the jet.

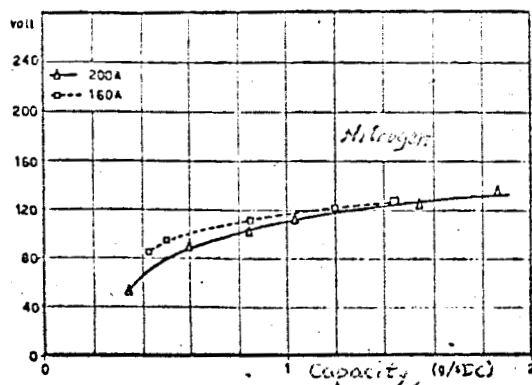


Figure 5. Voltage-capacity curve in the nitrogen arcjet.

Heat loss in both electrodes is indicated in figure 6 for hydrogen while figure 7 shows results obtained for nitrogen. In the analyses of these results consideration is given to the phenomenon of thermal exchange in both electrodes.

5.1. Cathode Loss.

Heating of the cathode is due chiefly to the existence of a high temperature heat zone in the base of the arc corresponding to the cathode spot where a fall in local voltage is observed which corresponds to the voltage required to extract from the metal the thermoelectrons making up the ionized column. The cathode drop of potential is a function of the nature of the metal, of the arc current, and of the operating gas. All other conditions being equal, this becomes a decreasing function of the current because, with the current increase and hence the local temperature increase of the cathode through the Joule effect, the energy necessary for extracting the thermoelectrons decreases; the power or energy dispersed in the cathode must result therefore approximately constant to the variation of the current. In fact, the cathode is also heated through irradiation of the arc column, while a certain cooling effect is noticed in the gas which touches it. These effects, however, should be secondary.

Experimentally, these considerations are confirmed in the case of nitrogen where the power dispersed in the cathode is in fact about constant to the

variation of both the current and the capacity. With hydrogen, however, a higher loss is noted with the current particularly at lower capacities of gas used, while the variation with the capacity is negligible. This anomaly, the subject of future research, is probably determined by the greater heat supplied to the cathode by hydrogen arc conduction, when hydrogen at low capacity (or energy) strikes entirely inside the chamber.

5.2. Anode Loss.

The thermal exchange between the chamber and the arc is closely connected with the dynamic flow characteristics of the gas in the nozzle; in the anode on the contact surface of the arc there is also observed a dispersion of power corresponding ^{to} the annulment of the thermoelectron kinetic energy, but /899 this loss is in large part less than the heat transmitted through convection by the operating gas. The thermal exchange between gas and metal is a function of the flux velocity; however, the presence of the vortex may noticeably influence results.

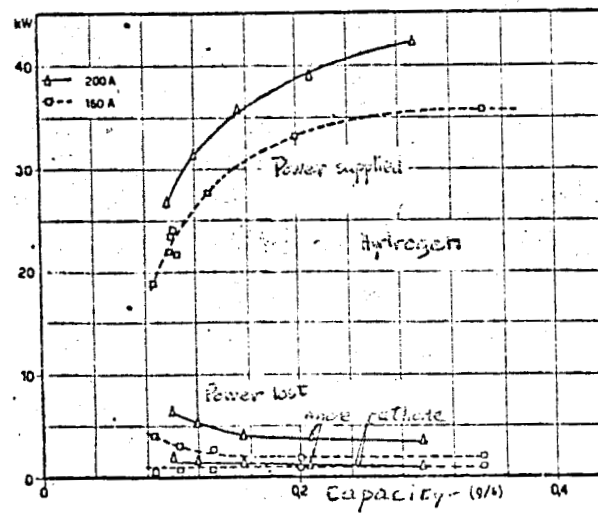


Figure 6. Heat lost in the electrodes of hydrogen arcjet.

As a matter of fact, it can be noted that in the case of nitrogen, when the capacity increases, the dissipated power remains approximately constant, equal to the current, while in the case of hydrogen, it decreases decidedly.

This anomalous behavior of hydrogen can be explained by a hypothesis analogous to that formulated for the cathode loss. It may furthermore be supposed that the jet, with the increased capacity, loses its homogeneity and is seen as a very hot nucleus at the axis surrounded by a gas veil which is relatively colder. This latter hypothesis could be confirmed by the considerable reduction of the losses which accompany the decrease in the current; in the case of nitrogen, the variation is very modest. It is hoped, nevertheless, that by continuing the present experiments this uncertain point will be cleared up.

6. Efficiency (yield).

Figure 8 illustrates the conversion gain for both gases, with variations in the current and in the capacity. The values of the efficiencies (yields) are very high and reach 90 percent for hydrogen, and 80 percent for nitrogen.

The minimum values are found at lower capacities, and are justifiable not only with a higher gas temperature from the moment that the molar heat content is practically constant throughout the field, but also under these circumstances the arc strikes entirely inside the chamber and the arc voltage is very low. Therefore, the relationship between the power supplied to the gas and the power dispersed in the electrodes is small.

As the capacity grows, the phenomenon of arc discharge already illustrated is verified; voltage consequently increases and hence the available power becomes greater while the loss in the electrodes remains about constant (or decreases, as is the case with hydrogen), through the protective action of

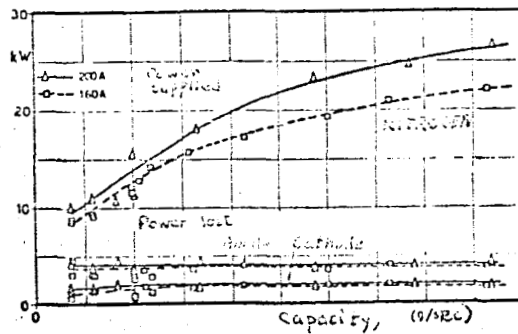


Figure 7. Heat lost in the electrodes of the nitrogen arcjet.

the vortex which thermally isolates the gas column ionized by the walls and limits the contact to the very ends of the arc.

Due to the noticeable nonhomogeneity of the gas jet at the exit of the arc chamber; for purposes of propulsion the addition of a mixing chamber would be required in front of the expansion nozzle. This was not done for the moment because the principal objectives of this research were to study the electrical characteristics of the arcjet driven by hydrogen and nitrogen, and to determine the degree of loss in the electrodes.

The introduction of a mixing chamber would account for a considerable reduction in efficiency. It is sufficient to note the great difference in these findings compared with those obtained in previous studies (ref. 5) using a much larger arc chamber and a more uniform jet.

7. Conclusions.

These studies, which almost complete the series of experiments conducted during four years at this School, have demonstrated the possibility of actuating a hydrogen-propelled arcjet which is stable and has a reduced electrode consumption. Thermal loss in this arcjet was evaluated by varying the operating conditions; thermal conversion gain was determined.

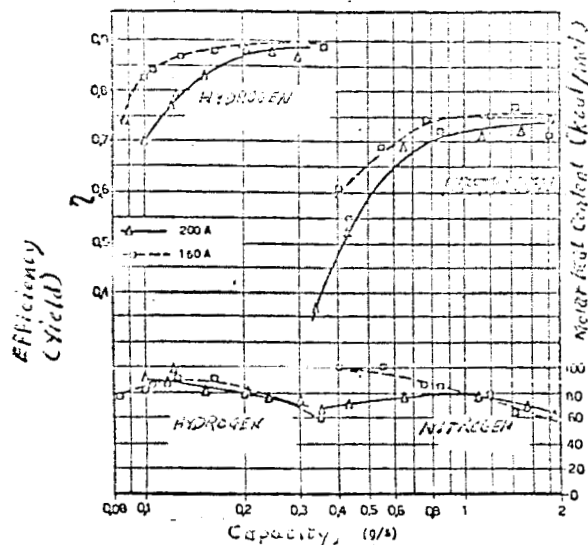


Figure 8. Efficiency (or yield) curve.

Based on these results, we intend to undertake a new series of experiments starting with the construction of a dynamometric board and, later, the development of a vacuum chamber, in order to complete the arcjet studies with measurements of true thrust and space similarity.

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